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Local variability of sedimentation rate in Lake Arendsee, Germany

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ABSTRACT

We measured the thickness and the dry weight of recently deposited sediment along several transects across Lake Arendsee in order to quantify the sedimentation rate and its local variability. As a time marker, we used an artificial marl layer that was deposited by a remediation program in the year 1995. A portion of the sediment deposited during the year was transported from the littoral and the top of the submerged hills to the foot of the slope, where we found the greatest deposition. Within the same lake, the deposited sediment layer varied by a factor of 4 between minimal and maximal values over the same time periods. Lake Arendsee is a holomictic and eutrophic lake with depletion of oxygen in summer time.

1. Introduction

In paleolimnology, the sediment deposition is a very important parameter. It can give information about the age of the sediment, e.g. by counting the varves, if the sediment is not disturbed by bioturbation (e.g. Nipkow, 1920; Negendank et al., 1990; Brauer et al., 2000; Zolitschka et al., 2000; Litt et al., 2001). The sedimentation rate can be used as an indicator for the human impact on the catchment area. The sedimentation rate increases when the catchment area is deforested and used for agriculture (Zolitschka, 1992). The sediment can also record the eutrophication history of a lake (e.g. Lami et al., 1994; Liukkonen et al., 1993; Schneider et al., 1990; Scharf, 1998). The investigation of the Lake Zürichsee in Switzerland was probably the first to show the relation between eutrophication of a lake by human settlement in the catchment area and change of sediment structure (Nipkow, 1920). In some lakes, the eutrophication is also indicated by annual calcareous laminae in lake sediments resulting from the biogenic precipitation of calcite by phytoplankton (Niessen and Sturm, 1987; Lami et al., 1994; Scharf, 1998; Hupfer and Lewandowski, 2005). Generally the sedimentation rate increases with the eutrophication of a lake (e.g. Niessen and Sturm, 1987; Schneider et al., 1990) as Nipkow (1920) has already shown.

In Lake Arendsee, we have the rare opportunity to quantify the sedimentation rate by a very easy method, so that we can show where the sedimentation rate is maximal and where it is minimal in this lake. In 2002 and 2003, we measured the sedimentation rate in several transects across the lake. The results are compared with seismic profiles.

2. Study site and methods

Lake Arendsee is located in the northern part of Germany (52° 53' N, 11° 28' E). This lake was formed by the dissolution of an underground salt dome (Gabriel and Rappsilber, 1999; Röhrig and Scharf, 2002). At the end of the last glacial period, the cover layers above the salt dome started to collapse in the western part of the lake. The collapse continued over the northern and southern parts of the salt dome. In 822 AD the central part of the cover layers also sank and was submerged in the lake water. Some submerged hills in the central parts of the lake are the residuals of the ancient earth surface (Scharf et al., 2009). Owing its existence to the dissolution of salt deposits beneath the present lake, Lake Arendsee has steep slopes (Fig. 1). The morphometrical and hydrological characteristics are summarized in Table 1. Lake Arendsee, with a maximum depth of 50 m, is stratified in summer; it is holomictic and monomictic in most years.

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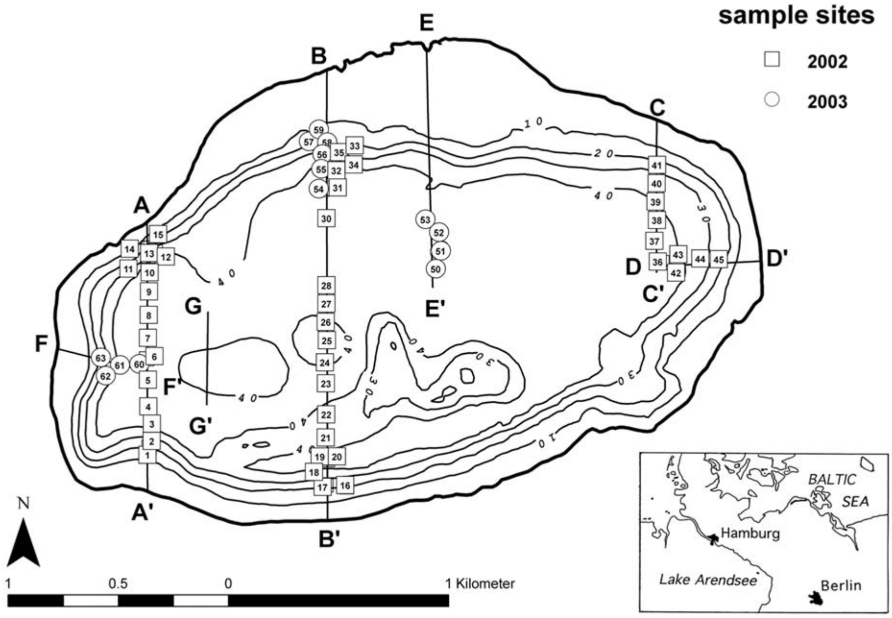

Fig. 1. Bathymetric map and drilling transects across Lake Arendsee in the years 2002 and 2003 for quantifying the sediment deposition. Profile G–G' is a part of a seismic profile (compare Fig. 6).

Table 1
Morphological and hydrological characteristics of Lake Arendsee (Rönicke et al., 1998).

Area A_0	5.1 km^2
Volume V	147×10^6 m^3
Maximum depth	48.7 m
Mean depth	28.9 m
Catchment area	29.8 km^2
Retention time	114 a

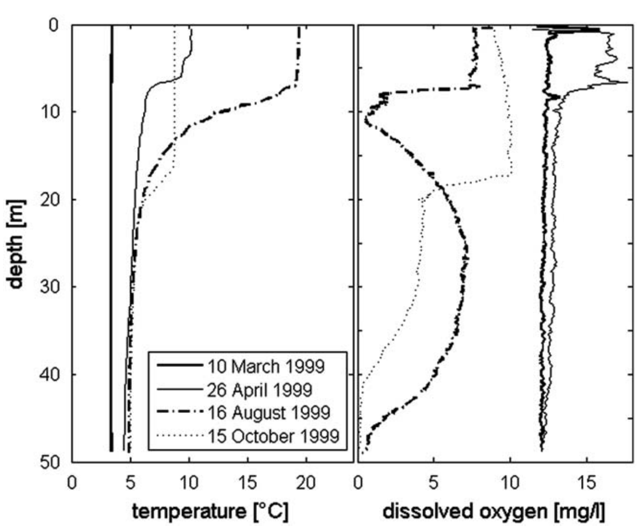

Fig. 2. Profiles of temperature (left panel), and concentration of dissolved oxygen (right panel) from March 1999 to November 1999 in Lake Arendsee.

For several decades, Lake Arendsee has been eutrophic (Klapper, 1992; Scharf, 1998). During the summer stratification, the lower part of the hypolimnion becomes depleted of oxygen (Fig. 2). There is no indication that the deep recirculation period would have been missing, or that the lake would tend towards meromixis (Boehrer and Schultze, 2008). At the end of summer, the oxygen-depleted zone increases from the bottom to a water depth of about 40 m (Fig. 2). Between 1992 and 1995, the macrozoobenthos only colonized Lake Arendsee down to a depth of about 25 m. During summer stagnation, a thick layer of sulfur bacteria exists on the bottom from the maximum depth to a water depth of about 25 m (Wilhelmy and Scharf, 1996). As a consequence, no bioturbation exists in the lower part of the profundal sediment.

Profiles of water properties were acquired by lowering a multiparameter probe (Ocean Seven, Idronaut, Italy) at a speed of about 20 cm s^{-1} through the water column. The probe carried sensors for pressure (depth), temperature, electrical conductivity, pH, chlorophyll fluorescence and turbidity. Oxygen measurements were corrected numerically for the response time of 7 s. Because especially the presence of oxygen is crucial for the establishment of the food-web, we display the 1999 annual cycle of oxygen profiles together with the profiles of temperature, which reflected the conditions of circulation and stratification periods (Fig. 2); typical features of a holomictic, eutrophic lake are revealed.

A remediation program was implemented in autumn of the year 1995 (Klapper, 1992, Rönicke et al., 1998). A natural deposit of marl at the northern shore was dug up and suspended in water. The mixture of marl and water was sprayed over the whole lake in order to expedite oligotrophication (Rönicke et al., 1998; Walpersdorf et al., 2004; Hupfer and Lewandowski, 2005). The material settled and formed a white layer, which served as a time marker for the presented investigation (Fig. 3). The artificial marl layer was clearly identifiable in sediment cores (see Fig. 3).

On 26th June 2002, 45 sediment cores were recovered (nos. 1–45 in Fig. 1) and on 4th April 2003 a further 14 cores (nos. 50–63 in Fig. 1). In 2002, we measured only the thickness of the deposit above the artificial marl layer in several transects across the lake (Fig. 1) by using a gravity corer with 60 mm diameter (UWITEC, Mondsee, Austria) (Danielopol and Niederreiter, 1990). The thickness of the sediment could be measured directly through the transparent core tube. In 2003, we additionally compared the thickness and the dry weight of the sediment younger than 1995. For this, the total sediment in the core tube above the artificial marl layer was collected in the field and dried

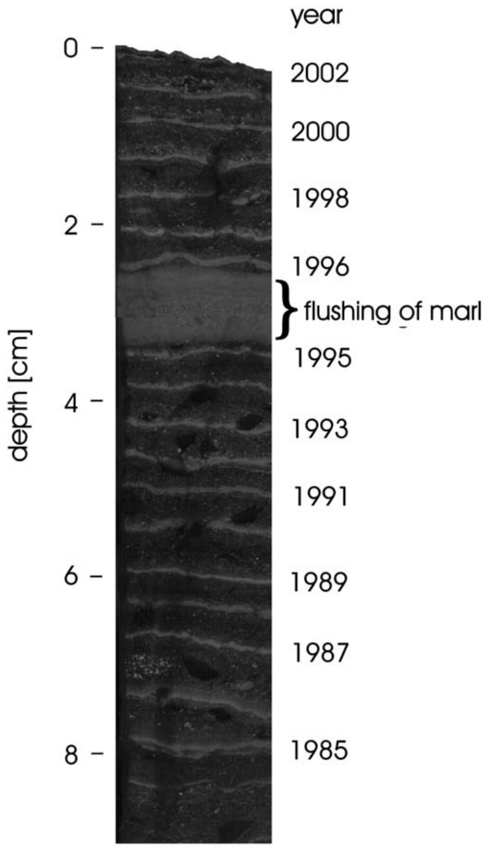

Fig. 3. Thin section of a sediment core from Lake Arendsee, prepared according to the method of Röhrig and Scharf (2006). The artificial marl layer is clearly identifiable. The core was taken in April 2002 in the eastern basin at a water depth of 46 m (sample site 37 in. Fig. 1).

at 105 °C (dry weight without water) and burned at 550 °C (loss on ignition for eliminating the organic carbon without destroying the carbonates, Dean, 1974) in the laboratory.

In April of 1997, seismic transects at intervals of about 200 m were measured across the whole Lake Arendsee with a chirp system (GeoChirp, high resolution, 1.5–11.5 kHz). Both transmitters and receivers were attached on a float behind a motor boat. 3 transects in east–west direction and 13 transects in north–south direction were taken. When the sediment contained gas the echo sounding was disturbed and did not mark the ancient sediment surface, as shown in Fig. 6 in the center of the basin.

3. Results

During March 1999, the lake experienced a full overturn (Fig. 2). The whole water column was well supplied with oxygen. At the beginning of the stratification period (late April), photosynthetic activity increased oxygen concentrations in the epilimnion beyond 100% of atmosphere equilibrium. Later during the summer stratification period (August), decomposition of organic material depleted the water of oxygen in the metalimnion and in the deepest layers of the hypolimnion. Deep recirculation late during the year (November) supplied oxygen to the deeper waters at a time when the anoxic zone had grown to a thickness of 10 m. Oxygen levels were low between 20 and 40 m depth, but there was no indication for a complete depletion. The situation was very similar in other years (e.g. year 2000, see Boehrer and Schultze, 2005).

Beside the artificial marl layer, the thin section shows some further white layers (Fig. 3). Clearly identifiable bands of alternating dark and light colored layers could be found. The white layers above and below the artificial marl layer were formed by calcium carbonate crystals, resulting from the biogenic precipitation, which occurs in Lake Arendsee each year in the time from June to July (Scharf, 1998; Hupfer and Lewandowski, 2005). The intermediate layers owe their dark color to a high content of organic material. The number of bands above the marl layer corresponded with the number of annual cycles since the remediation in 1995. Hence we dealt with annual sediment layers, so-called varves.

White bands were annotated with their year of formation (Fig. 3). Also the calcium carbonate layers below the artificial marl layer, i.e. prior to 1995, could be dated. Varves could be identified back to the year 1955, which coincided with the time when eutrophication intensified in Lake Arendsee. This time information was confirmed by ^{137}Cs investigations (Scharf, 1998; Hupfer and Lewandowski, 2005).

According to the thin section shown in Fig. 3, the sedimentation rate amounted to about 4.4 mm yr^{-1} in this part of the lake (coring point 37 in Fig. 1). It did not vary significantly after the spraying of the marl. All collected cores of several transects (Fig. 1) showed the same features as visible in the thin section above (Fig. 3), but the sedimentation rate varied.

On average, between 1995 and 2002 about 40 mm of sediment was deposited, which corresponds to a sedimentation rate of 5.7 mm yr^{-1}. Some variations of the deposited layer thickness since 1995 could be observed, ranging from 20–80 mm. On the submersed hills in the middle of the lake, the deposition was less, as shown in Fig. 4, while the deposition rate was greater in the valleys between the hills. Along the foot of the slopes, we found a maximum recent sediment layer of up to 80 mm at water depths between 35 and 20 m. Between the shore and a depth of about 20 m, we found chironomid larvae (Diptera) together with other animals in the core tubes, which had disturbed the lamination to such an extent that we could not identify the artificial marl layer by visual inspection at shallow depths.

The sediment thickness and the accumulated weights over the artificial marl layer have been measured in 2003 (Fig. 5). In transect E–E' in the middle of the lake (Fig. 1), only small differences in the sediment thickness and in the dry weights existed. Sample site 50 (47 m water depth) had the highest

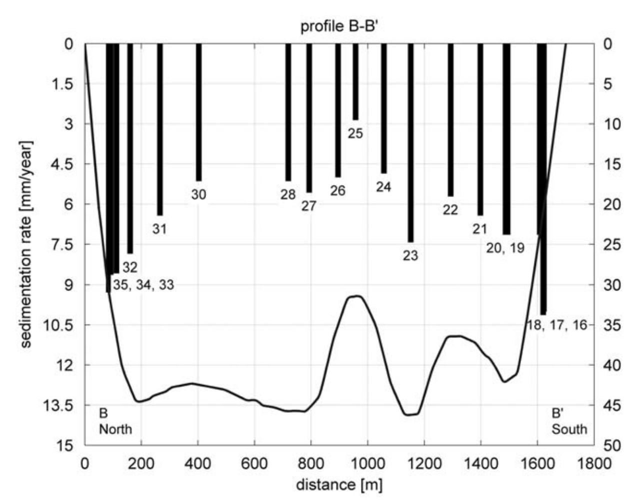

Fig. 4. The yearly sedimentation rate on transect B–B' with sample sites 16–35 calculated by sediment above the artificial marl layer divided by seven years (time between the remediation program in 1995 and core sampling in 2002). The bathymetry is given along the transect from north to south.

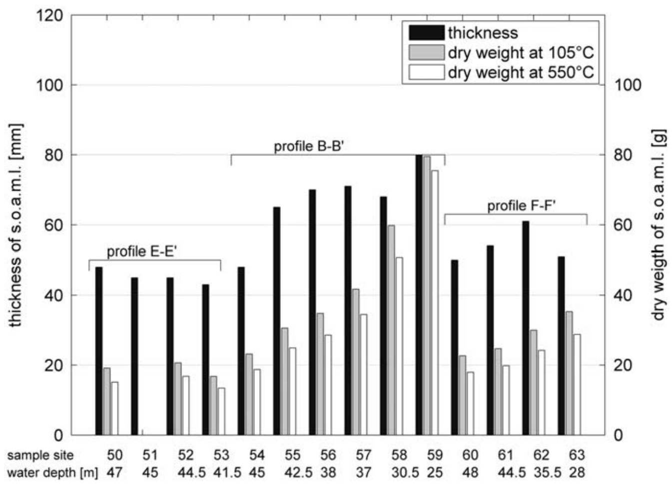

Fig. 5. Comparison between thickness and dry weight at 105 and 550 °C of the sediment above the artificial marl layer (s.o.a.m.l.) in Lake Arendsee. At the sample site 51, the dry weights were not measured.

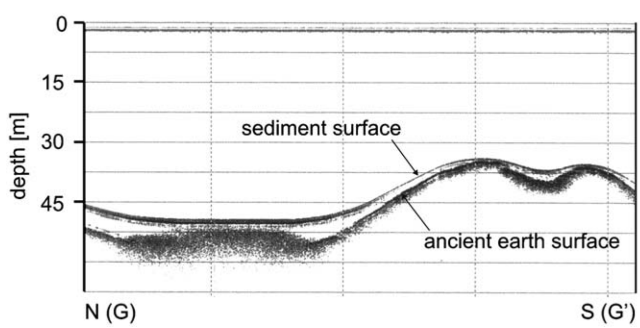

Fig. 6. Seismic profile G–G' of Lake Arendsee, taken with a chirp system (GeoChirp, high resolution, 1.5–11.5 kHz). For the position of the profile see Fig. 1.

deposition rate within this profile, sample site 53 (41.5 m) the lowest. The values of profile E–E' were lower than those from the slopes and the foot of the slopes (profile B–B' and profile F–F'). In profile B–B' at the northern slope, the thickness and the dry weights of the sediment since 1995 of the sample 54 were similar to those of profile E–E'. But at the foot of the slope and on the lower part of the slope itself, the values were distinctly higher. Especially the dry weights increased towards shallower water depths. In the profile F–F' at the eastern slope, the results were similar to profile B–B', but the sediment deposition rate was lower.

The seismic profiles (Fig. 6) confirmed that the deposition was small on the top of the hills, but increased in the direction of the foot of the slopes. There was no information about the deposition in the center of the basin, because sound reflection at gas bubbles inside the sediment disturbed the echo.

4. Discussion

Measurements of temperature and dissolved oxygen (Fig. 2) were performed at the deepest location in the western part of Lake Arendsee (near sample site 8 in Fig. 1). At the end of the summer stagnation, the water layer from 40–50 m depth was completely depleted of oxygen. At depths between 20 and 40 m, most of the oxygen had been consumed, while 4 mg L^{-1} still remained in the pelagic zone. However, the presence of sulfur bacteria and the absence of macrozoobenthos (Wilhelmy and Scharf, 1996) indicated that the situation directly above the sediment was different at the same water depth. Oxygen depletion at the sediment surface explained the presence of clearly visible varves below a water depth of 20 m.

Wind acted on the surface water and induced surface waves and currents. Two major zones of resuspension in the lake were suspected: the main zone of resuspension above the wave base and the zone of possible resuspension, e.g. by internal seiches below the wave base (Bloesch, 1995). Resuspension occurred when the current-induced bottom shear stress was sufficient to disrupt the cohesion of the bottom sediments (Bloesch, 1995).

We assume that a portion of the sediment deposited during the year was resuspended, especially from the littoral and from the top of the hills, and transported to greater depths of the lake. Resuspension and relocation of recent sediment may also have occurred due to seiche-induced currents during the stratification period. The low deposition on the top of the hills was very well reflected in coring profiles (Fig. 4) and in seismic profile (Fig. 6). This resuspended sediment was deposited in deeper areas, i.e. especially in the valleys between the hills and at the foot of the slopes. Here we found the highest deposition, even exceeding the sediment deposition in the central basin and at the deepest location (profiles E–E', B–B' and F–F' in Fig. 5). The dry weight and the weight after burning at 550 °C decreased from the littoral to the profundal (Fig. 5). This fact implicated selective transport of lighter material. The heavy matter was redeposited immediately. The investigation of the ostracods (Crustacea) of Lake Arendsee confirmed this fact: while heavy valves of the adults, e.g. of *Candona candida*, remained in the littoral and upper profundal, light valves of juveniles were transported to the lower profundal, where the species did not live (Scharf, 1998). At the lower part of the slopes, dry weight was less despite nearly the same thickness of the sediment (compare sample 55 with sample 58 in Fig. 5).

The non-uniform distribution of the sediment deposits will smooth out the lake bottom topography, as higher elevations receive less material, while edges are filled faster. In contrast to deep meromictic maar lakes, the shallow and holomictic maar lakes, where the circulation currents reach the lake bottom, have a smooth transition from the bottom to the slope (Scharf and Menn, 1992).

5. Conclusions

This study shows that the oxygen depletion in Lake Arendsee supports the formation of varves. Alternating layers of calcium carbonate and mainly organic material were observed. Besides ^{137}Cs-measurements (Scharf, 1998; Hupfer and Lewandowski, 2005), the year of formation could be derived from an artificially imported marl layer. Varves could be identified back until the year 1955, when eutrophication of Lake Arendsee was intensified. Within the same lake, the deposited sediment layer varied by a factor of 4 between minimal and maximal values over the same time periods. The variability was clearly correlated with the morphometry of the lake. *Vice versa*, the preferred sediment deposition in depressions smooths the morphometry of a lake.

When selecting core sites for paleolimnological studies, the presented information can prove helpful. In general, the basins of lake have the highest sedimentation, which is confirmed for Lake Arendsee by Fig. 6 (seismic profile). Therefore concerning on the purpose of a drilling project, the highest resolution will be provided by a core from the basin. A core with older sediment and low resolution is to be expected on the submerged hills or rises.

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